Modern HTR Technology
With Process Heat Applications

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What is a High Temperature Reactor (HTR) Today?

- **Small thermal reactor – 400-600 MWth**
- **Gas cooled – helium**
- **High temperature – 750-950ºC coolant outlet temperature**
- **Graphite moderated**
- **Particle fuel core – pebble or prismatic design**
- **Passive safety with inherent characteristics**

GENERATION IV
nuclear energy systems

Very High Temperature Reactor (VHTR)

Historical Look – Genesis

- United Kingdom
  - Developmental
    - Dragon (20 MWth) 1964-1977
  - Large commercial program (Magnox and AGR) but CO_2 cooled
- Germany (Pebble)
  - Developmental
    - AVR (15 MWe) 1967-1989
  - Commercial Demonstration
    - THTR (300 MWe) 1985-1989
- United States (Prismatic)
  - Developmental
    - Peach Bottom 1 (40 MWe) 1967-1974
  - Commercial Demonstration
    - Fort St Vrain (330 MWe) 1979-1989

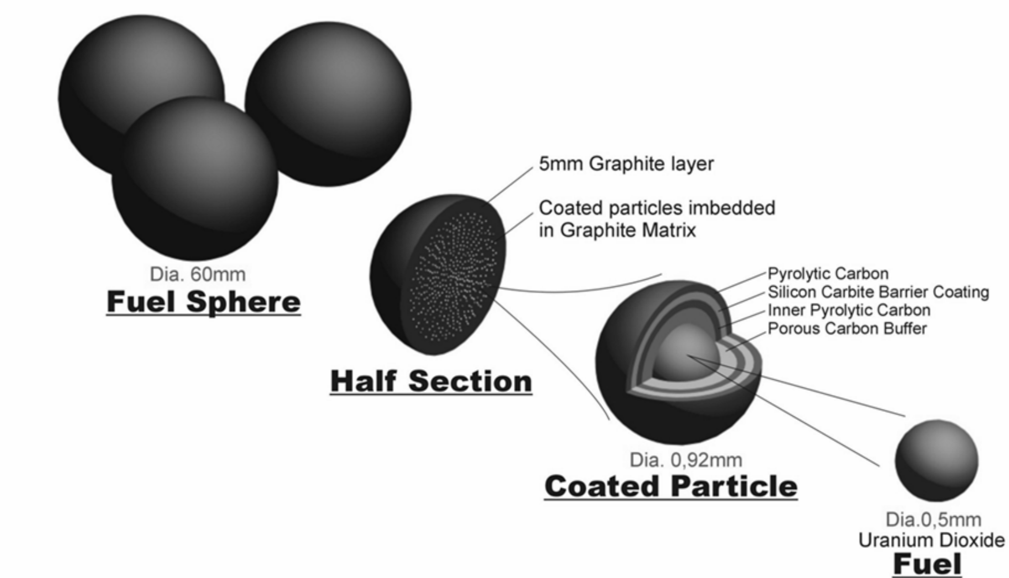
AVR

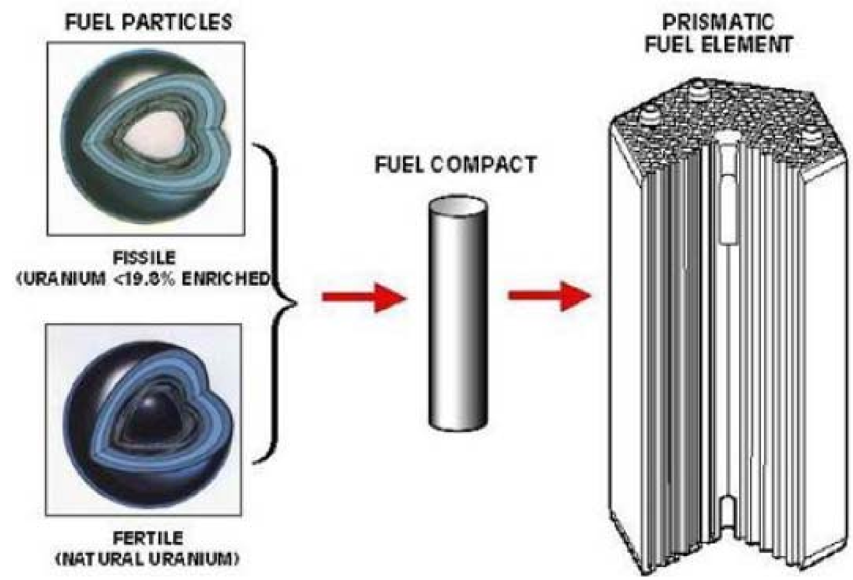
Peach Bottom 1

What Are the Design Options?

- Prismatic versus Pebble Fuel
  - Fixed vs Dynamic Core
  - Periodic vs On-line Refueling
  - Burnable Poison Control vs Fuel Inventory Control of Excess Reactivity
  - Multiple fuel types vs single fuel type
- Direct versus Indirect Cycles
  - Direct Cycle for Electricity
  - Indirect Cycle for flexible process heat and co-generation options

HTR Fuel Forms





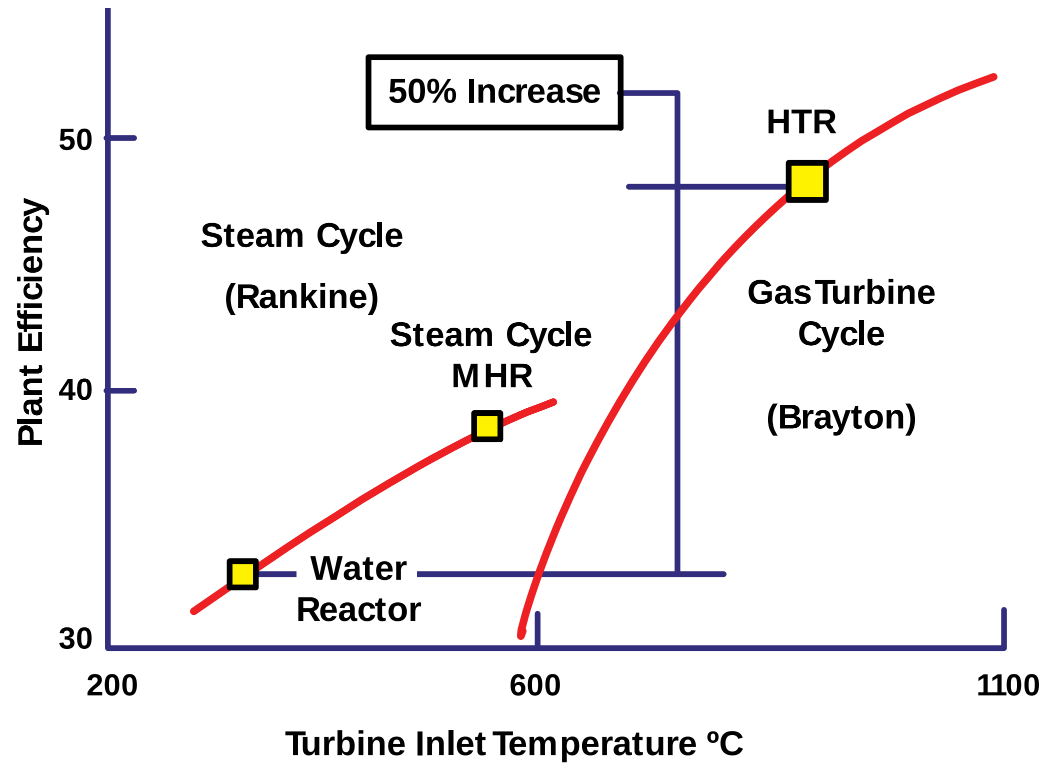
Pebble Design **Prismatic Design**

The Promise of HTRs

- High Thermal Efficiency
- Enhanced Safety allowing Close-in Siting
- Better Fuel Utilization
- Improved Waste Disposal
- Enhanced Proliferation Resistance
- Competitive Economics
- Process Heat Applications with no CO_2 emissions

High Thermal Efficiency – Electricity

- Light Water Reactors (LWRs)
  - Utilize Steam Rankine Cycle
  - Coolant Outlet Temperature 315-330ºC
  - Typical thermal efficiency value 33-35%
- High Temperature Reactors (HTRs)
  - Utilize Rankine or Brayton Cycle
  - Coolant Outlet Temperature 750-900ºC
  - Typical thermal efficiency value 41-48%



Enhanced Safety

- Coated particle fuel as the principal fission product barrier
- Single phase inert coolant with no reactivity effects
- Large negative temperature coefficient throughout core life
- High reactor heat capacity with very long response/ transient times and continued structural integrity
- Large fuel temperature margins
- Low power density and low decay heat in large uninsulated reactor vessel
- Annular Core geometry with large surface area
- On-line refueling (pebble) with very low excess reactivity
- Passive decay heat removal via convection, conduction, and radiation through components to concrete heat sink

Passive Safety with Virtually No Core Melt

Better Fuel Utilization

- Low power density
- Good neutron spectrum with minimal neutron self shielding
- Minimal neutron parasitic absorption from core structures
- On-line refueling (pebble) that minimizes core fission product burden
- Particle fuel capable of high burnup (>> LWRs)
- Flexible fuel cycle (UO_2, ThO_2, PuO_2, UCO, etc.)

Improved Fuel Economics

Improved Waste Disposal

- Particle fuel is self-encapsulating, i.e., contains fission products inside particle coatings
- Very stable ceramic fuel form provides long term stability in waste repository
- Low decay heat power density allows air cooling after discharge from the reactor
- Easily amenable to consolidation by removal of matrix graphite
- High burnup means less waste per volume of heavy metal
- Structural graphite decontamination and recycle are possible to reduce disposal burden

Enhanced Proliferation Resistance

- High fuel burnup leaves small quantities of plutonium at discharge with poor isotopics
- Low loading of fuel material in graphite matrix requires diversion of large physical quantities to be a significant material risk
- Coated particle barriers are difficult to remove
- Totally closed fuel handling and storage system (pebble) makes diversion easy to detect

Compatible with International Goals

Today’s Major HTR Programs

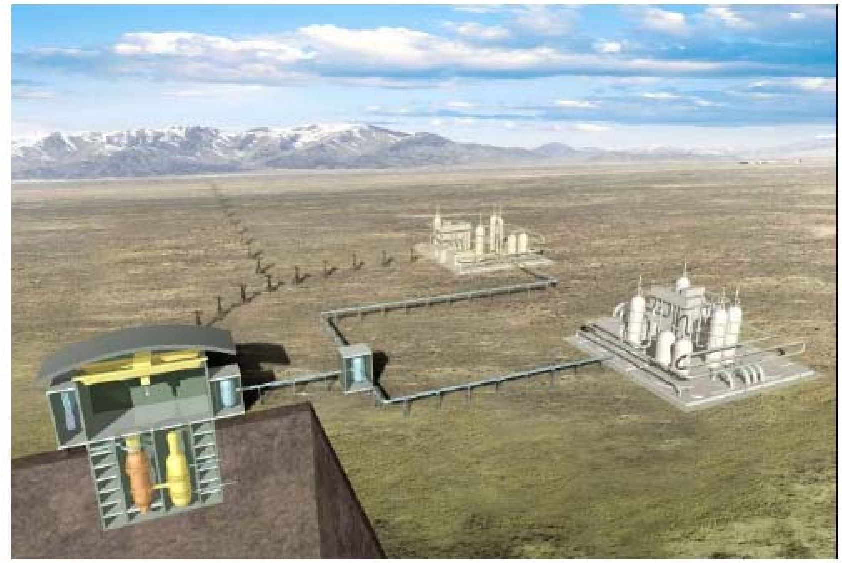
- China
  - Operating 10 MWth pebble bed fuel prototype; initial criticality 2000
  - Commercial electricity demonstration program (HTR-PM) ongoing; twin unit 200 MWe total; scheduled for operation 2014
- Japan
  - Operating 30 MWth prismatic fuel prototype; initial criticality 2000; provides heat source for H_2 generation development
  - No commercial program
- South Africa
  - Commercial electricity demonstration program (PBMR) ongoing; single unit 165 MWe; scheduled for operation 2014
- United States
  - Commercial process heat demonstration program (NGNP) initiated

HTR-10 (China)

HTTR (Japan)

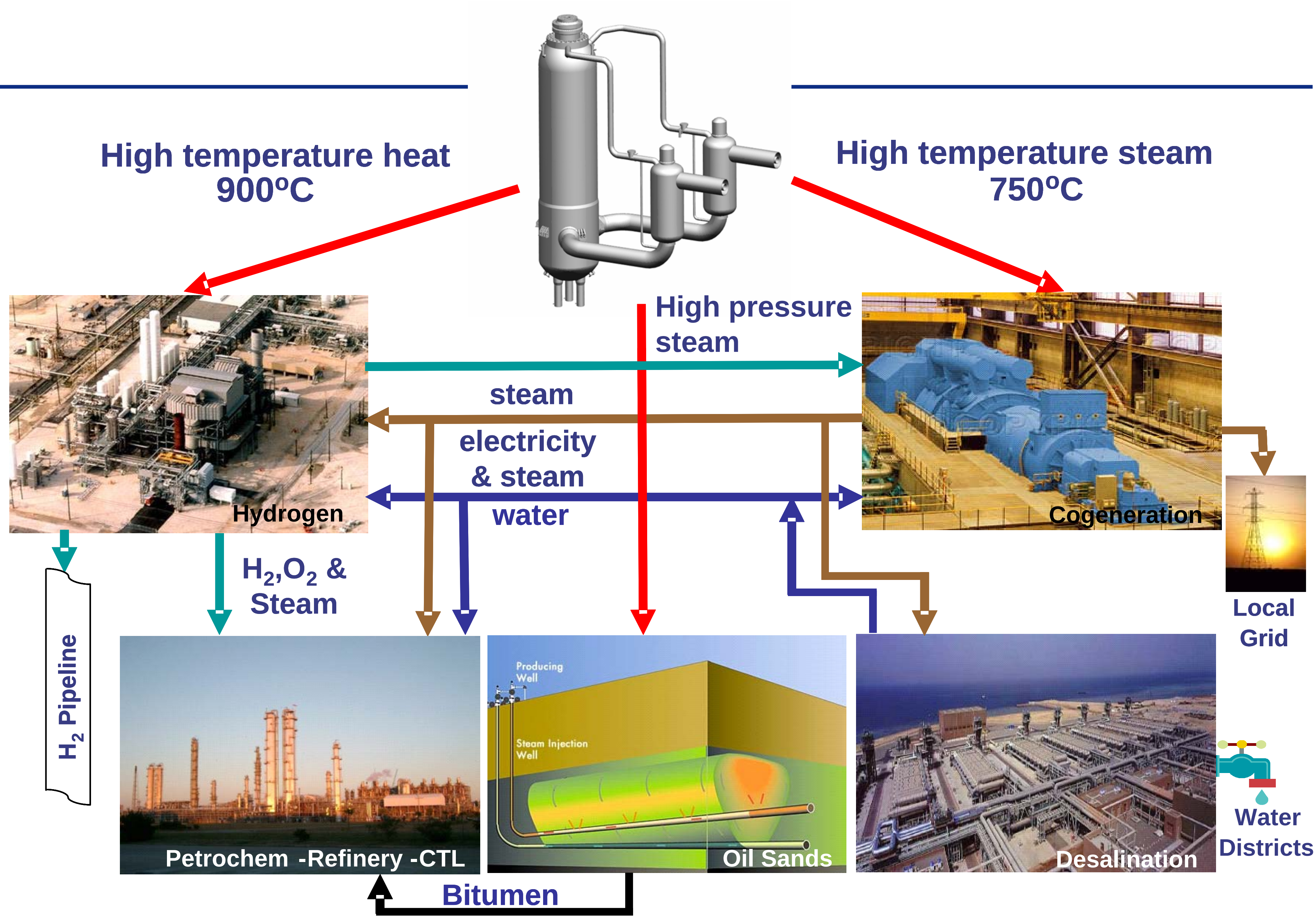
U.S. Next Generation Nuclear Plant (NGNP)

- **Authorized under US Energy Policy Act of 2005**
- **Co-generation of electricity and H_2 mission**
- **Three teams awarded contracts 9/2006**
- **Generation IV R&D ongoing**
- **Construction start 2014-2015; criticality 2019 (proposed)**
- **Shift in Focus and Plan per Industry/Market Consensus**
  - **Industry owned with DOE cost share; process steam cogeneration for first-of-fleet demonstration plant**
  - **Parallel development and demonstration of higher temperature technologies, e.g., H_2 production, at INL – adaptability without another nuclear demonstration**
- **RFIs and EOIs Submitted in June 2008**



Next Generation Nuclear Plant (NGNP)

Process Heat Markets - Path to Hydrogen



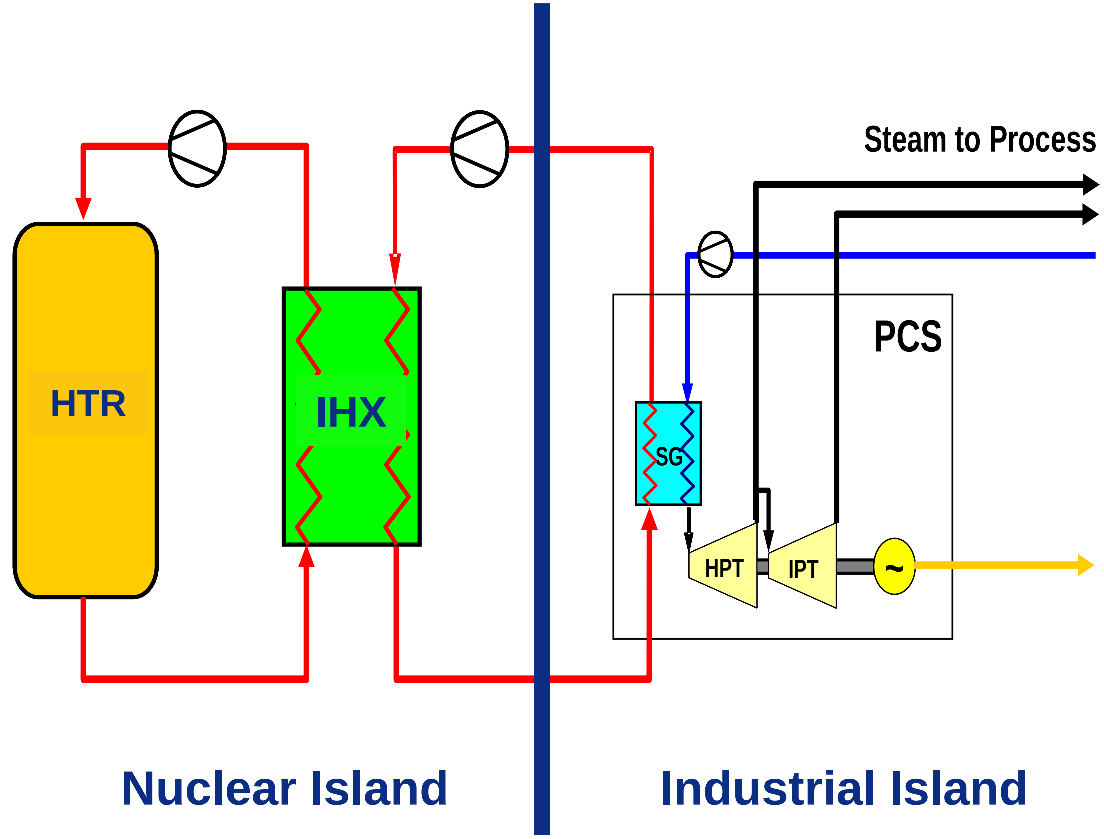
HTR Process Heat Fundamentals

- High process heat temperatures enable broad applicability
- Smaller plant size matches process heat energy needs
- Safety approach allows close-in siting to process application facilities
- Nuclear energy replaces premium fossil fuel (e.g., natural gas) that has uncertain availability and cost
- Opportunity to substitute abundant domestic coal resources for imported oil through CTL conversion
- Directly addresses green house gas emissions and hedges against future carbon taxes

Process Heat Plant Licensing Considerations

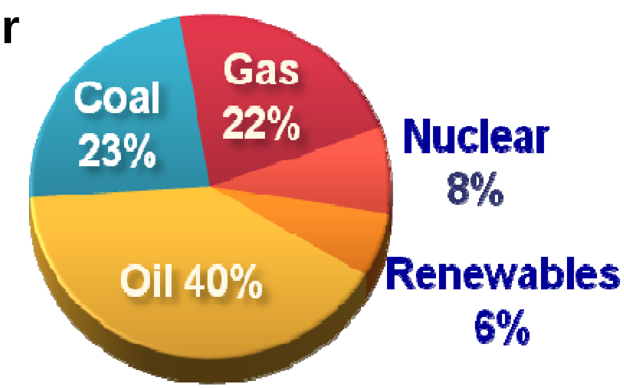
- **Co-locating nuclear and industrial facilities creates some unique challenges:**

  - ✓ **New operational hazards and threats to each side**
  - ✓ **Regulatory jurisdictional conflict potential**
  - ✓ **Potentially costly separation provisions**
  - ✓ **Design reliability (N-x) and operational cycle demands**
  - ✓ **Emergency planning**



What's Different – Future Opportunities

- Approach to economics
  - Smaller power increments; grid tariff not depressed
  - Less financial risk because of investment size
  - Short construction schedule; modular factory construction
- Deployment for electricity generation
  - Distributed power – reduced grid investment
  - Site flexibility – lower thermal heat waste and lower cooling requirements
- Process heat applications
  - Re-powering of chemical plants and refineries
  - Oil sands recovery and upgrading
  - Hydrogen generation
  - Coal-to-liquids conversion
  - Desalination
  - etc.



U.S. Energy Consumption

HTR Opportunities are Endless!